

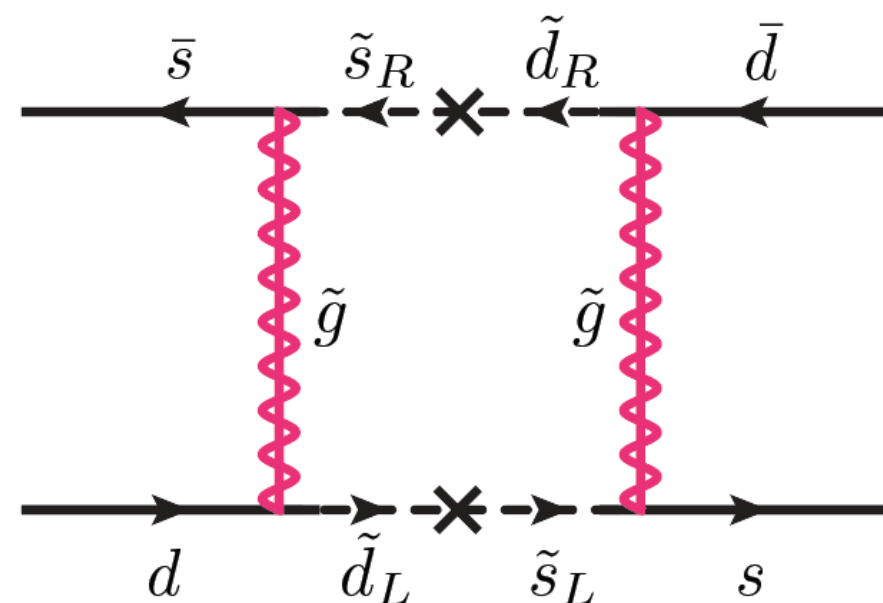
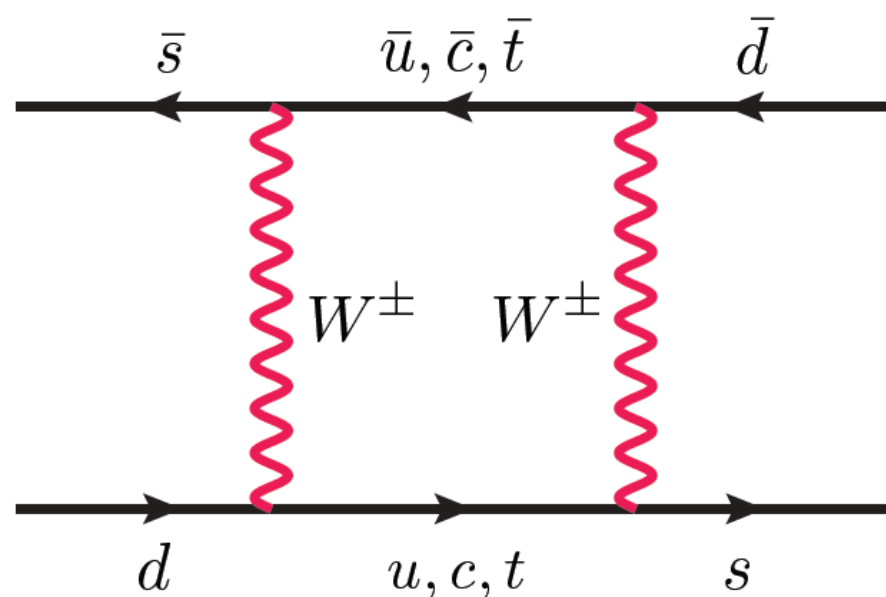
The CKM matrix and flavor physics from lattice QCD

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Why study flavor physics?

- ◆ Most extensions of the Standard Model contain new CP-violating phases and new quark-flavor changing interactions
 - ❖ \Rightarrow **We expect new physics effects in the quark flavor sector**
- ◆ The flavor sector is sensitive to physics at very high scales
 - ❖ New particles will typically appear in loop-level processes such as neutral kaon mixing:



- ◆ \Rightarrow We may see evidence for new physics in the flavor sector before we produce non-Standard Model particles directly at the LHC!

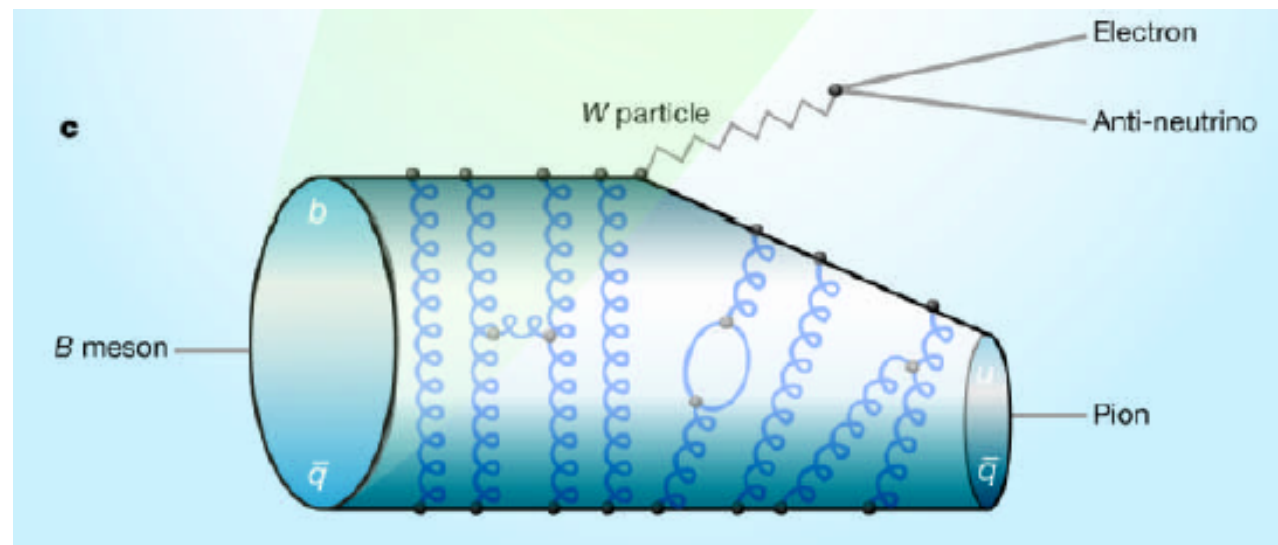
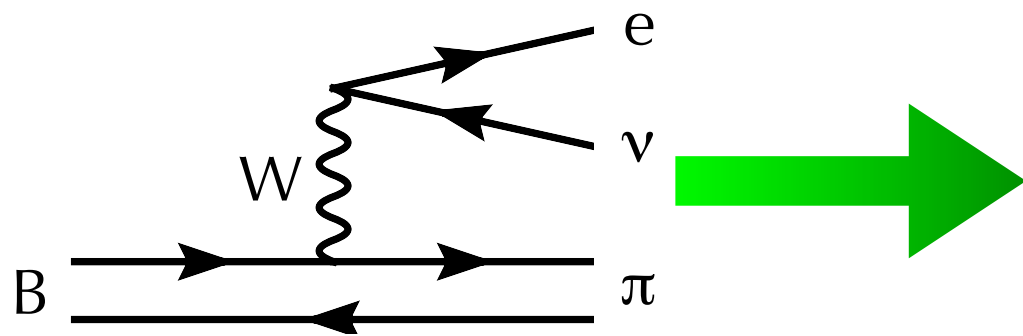
Lattice QCD and precision flavor physics

- ◆ Experiments have been pouring out data to pin down the CKM matrix elements but lattice calculations are needed to interpret many of their results

❖ Schematically, $\text{EXPT.} = \text{PT} \times \text{CKM} \times \text{LATTICE}$



- ◆ In order to accurately describe weak interactions involving quarks, must include effects of confining quarks into hadrons:



- ◆ Typically absorb nonperturbative QCD effects into quantities such as decay constants, form factors, and bag-parameters which we must compute in lattice QCD
- ◆ **Precise lattice QCD calculations of hadronic weak matrix elements are critical to maximize the scientific output of the experimental high-energy physics program**

Lattice QCD constraints on the CKM matrix

$$\left(\begin{array}{ccc} V_{ud} & V_{us} & V_{ub} \\ \pi \rightarrow l\nu & K \rightarrow \pi l\nu & B \rightarrow \pi l\nu \\ V_{cd} & V_{cs} & V_{cb} \\ D \rightarrow l\nu & D_s \rightarrow l\nu & B \rightarrow D l\nu \\ D \rightarrow \pi l\nu & D \rightarrow K l\nu & B \rightarrow D^* l\nu \\ V_{td} & V_{ts} & V_{tb} \\ \langle B_d | \bar{B}_d \rangle & \langle B_s | \bar{B}_s \rangle & \end{array} \right)$$

Lattice QCD constraints on the CKM matrix

◆ “Gold-plated” lattice processes allow the determination of most CKM matrix elements:

- ❖ 1 hadron in initial state;
0 or 1 hadron in final state
- ❖ Stable (or narrow
and far from threshold)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \pi \rightarrow l\nu & K \rightarrow \pi l\nu & B \rightarrow \pi l\nu \\ V_{cd} & V_{cs} & V_{cb} \\ D \rightarrow l\nu & D_s \rightarrow l\nu & B \rightarrow D l\nu \\ D \rightarrow \pi l\nu & D \rightarrow K l\nu & B \rightarrow D^* l\nu \\ V_{td} & V_{ts} & V_{tb} \\ \langle B_d | \bar{B}_d \rangle & \langle B_s | \bar{B}_s \rangle & \end{pmatrix}$$

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♦ Members of the BNL high-energy theory group are currently working on the quantities that are **circled in PINK**

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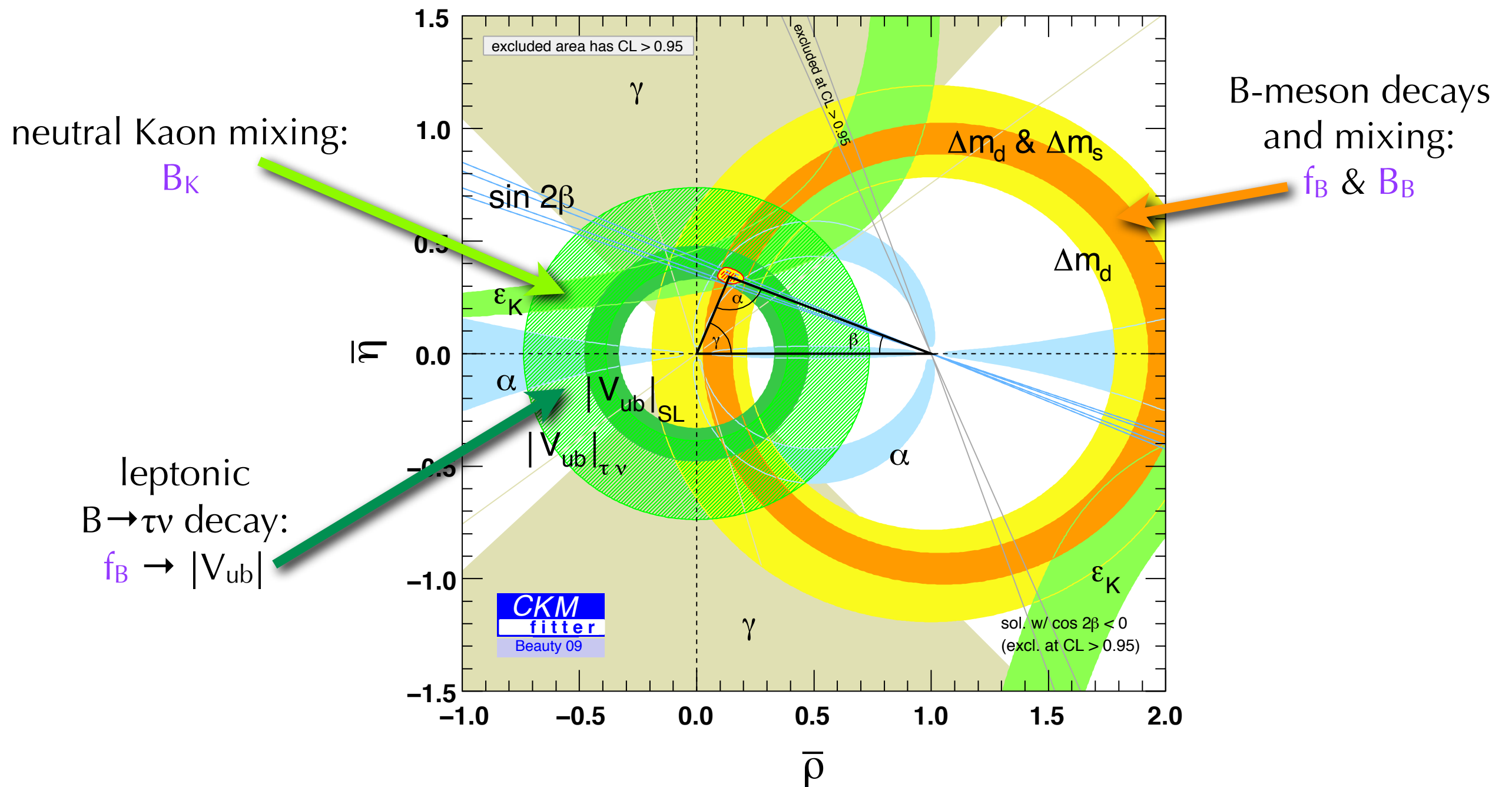
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 \end{pmatrix}$$

- ◆ Members of the BNL high-energy theory group are currently working on the quantities that are **circled in PINK**
- ◆ Our colleagues in the RBC Collaboration are working on those **circled in PURPLE**

Lattice QCD inputs to the unitarity triangle

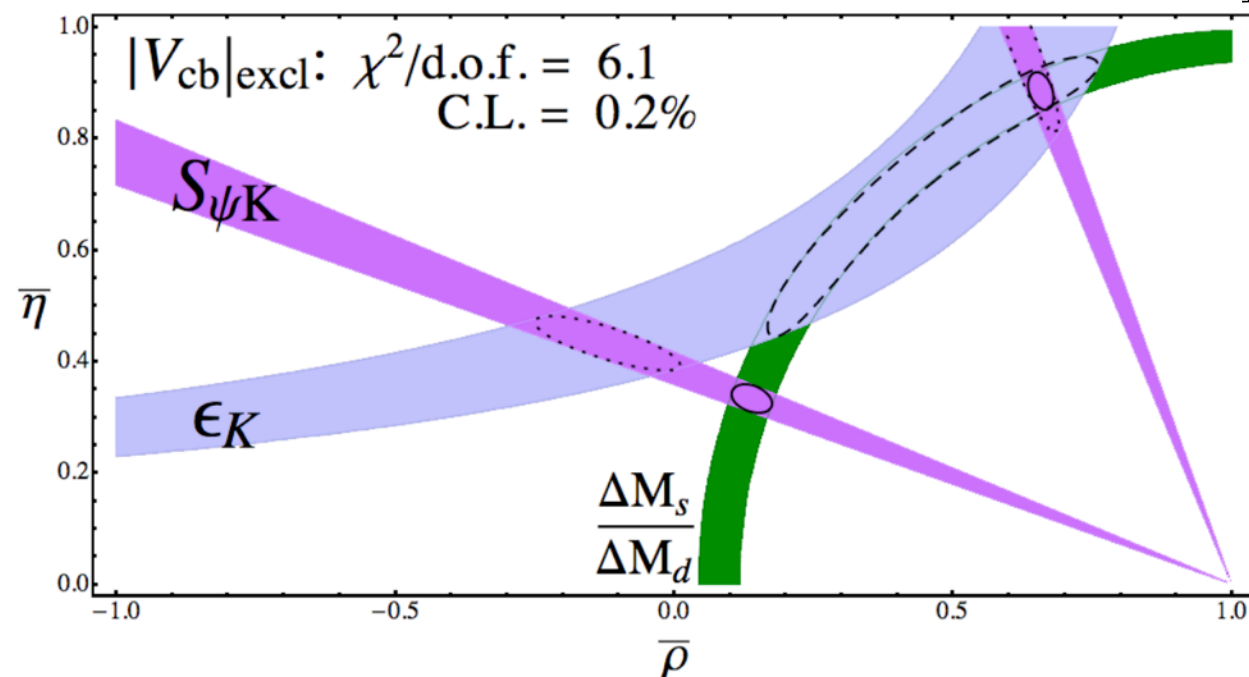
- ✦ Many constraints on the unitarity triangle require lattice QCD calculations of hadronic weak matrix elements
- ✦ Members of the BNL high-energy theory group are currently computing **several key inputs**:



Hints of new physics in the flavor sector...

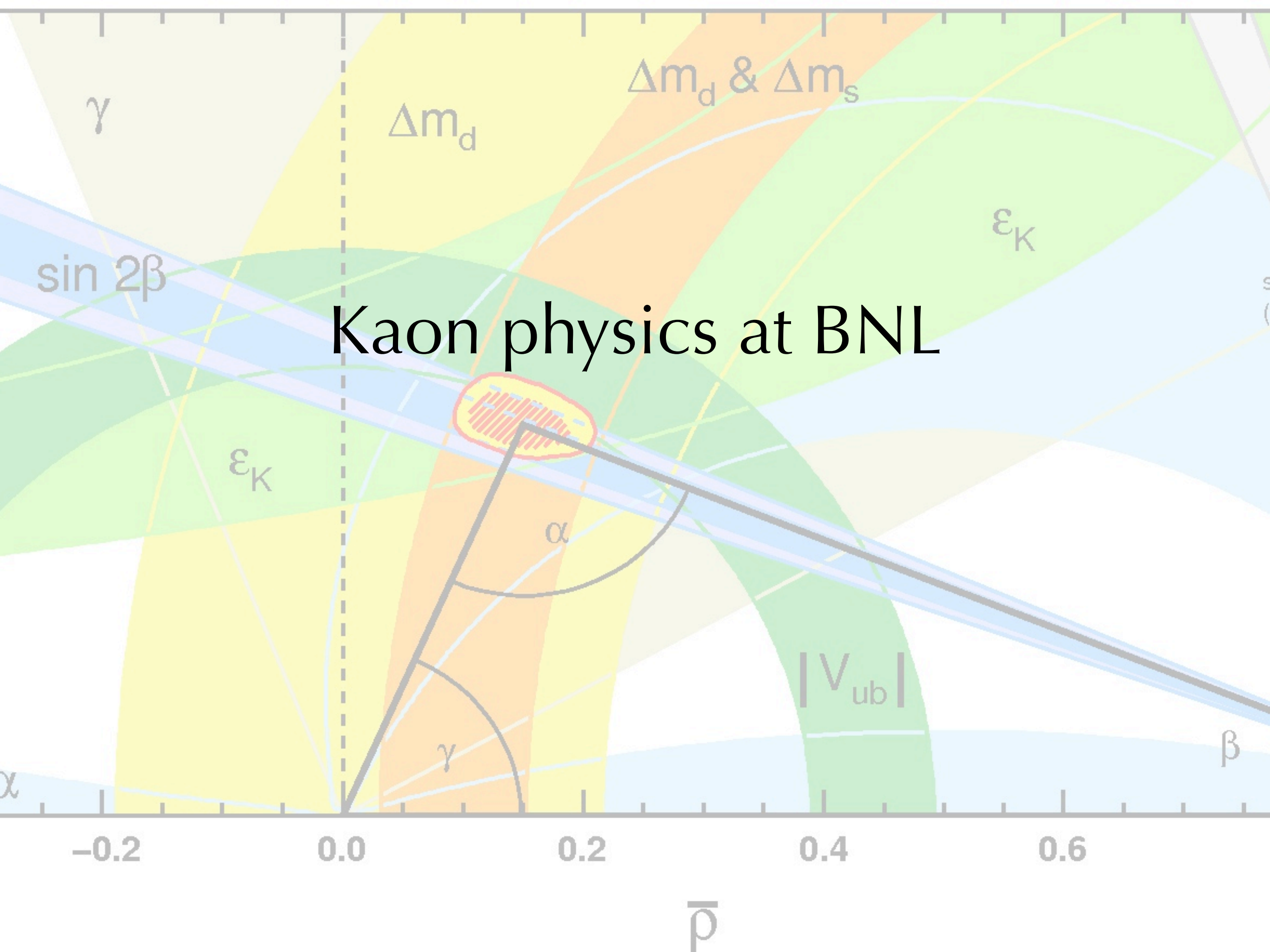
- ◆ If we omit the UT constraints from α , γ , and $|V_{ub}|$, it is easy to see that **there is a 2-3 σ tension between the constraints from ϵ_K , $\Delta M_s/\Delta M_d$, and $\sin(2\beta)$** [Lunghi & Soni, arXiv:0803.4340]

[Laiho, Lunghi, RV,
arXiv:0910.2928]



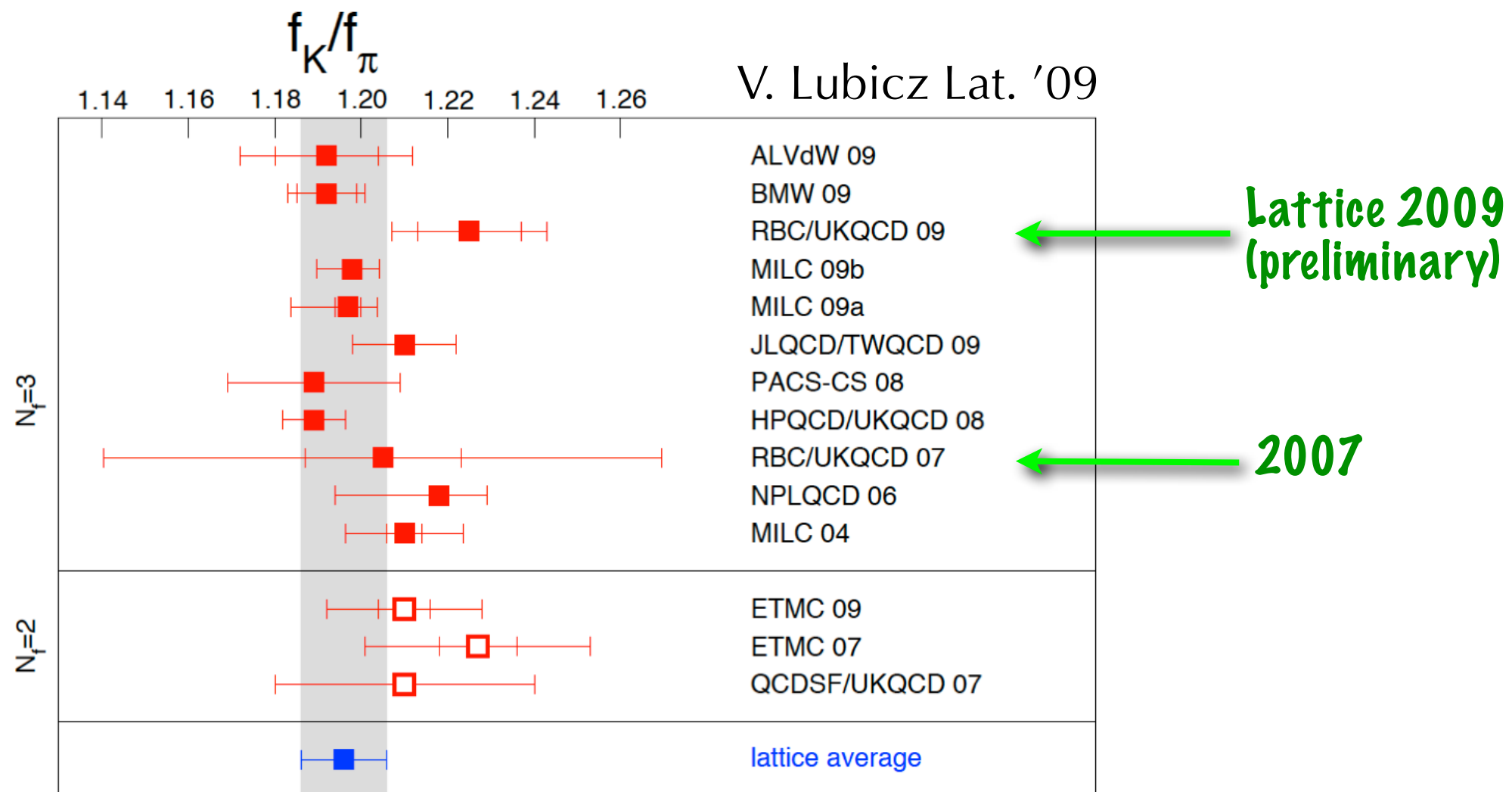
- ◆ There is also a 2.4 σ tension between the experimentally-measured $B \rightarrow \tau \nu$ branching fraction and the Standard Model prediction [CKMfitter, Beauty '09]

Members of the BNL high-energy theory group are calculating all of the hadronic weak matrix elements necessary for probing these hints of new physics in the flavor sector



f_K/f_π (RBC/UKQCD)

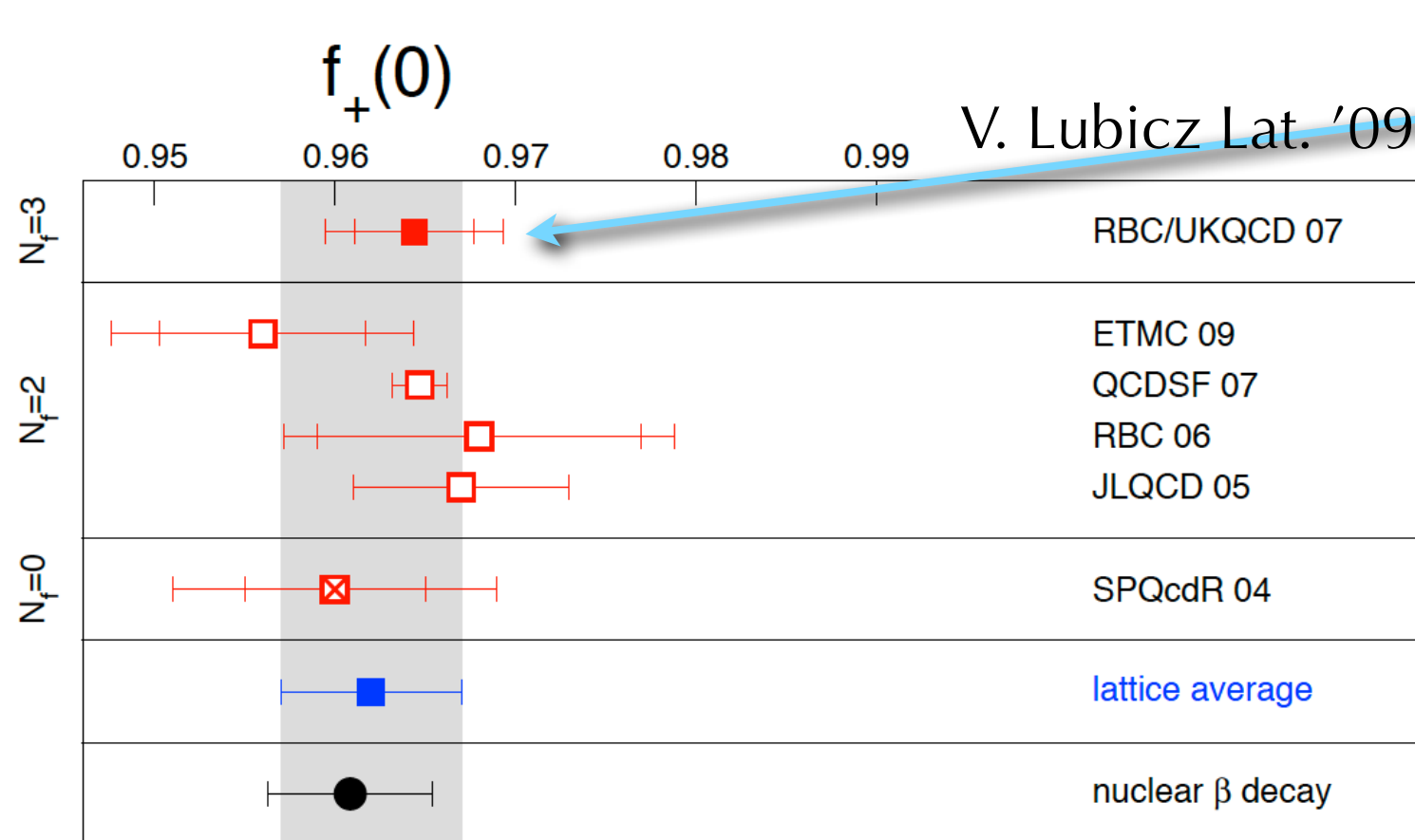
- ♦ The ratio f_K/f_π allows a precise determination of $|V_{ud}|/|V_{us}|$ [**Marciano**]
- ♦ In the past year, RBC/UKQCD have added data at a second lattice spacing and reduced their errors significantly



- ❖ *New preliminary result is competitive with other three-flavor lattice calculations*

$K \rightarrow \pi \ell \nu$ semileptonic form factor (RBC/UKQCD)

- Experiments measure the product of the form factor times the relevant CKM matrix element, $f_+(0) \times |V_{us}| = 0.2166(5)$, to 0.2% accuracy
 - \Rightarrow Need lattice calculation of form factor to obtain $|V_{us}|$
- In 2008, the RBC/UKQCD Collaborations published the first realistic calculation of the $K \rightarrow \pi \ell \nu$ form factor which includes the effects of the u, d, and s “sea” quarks

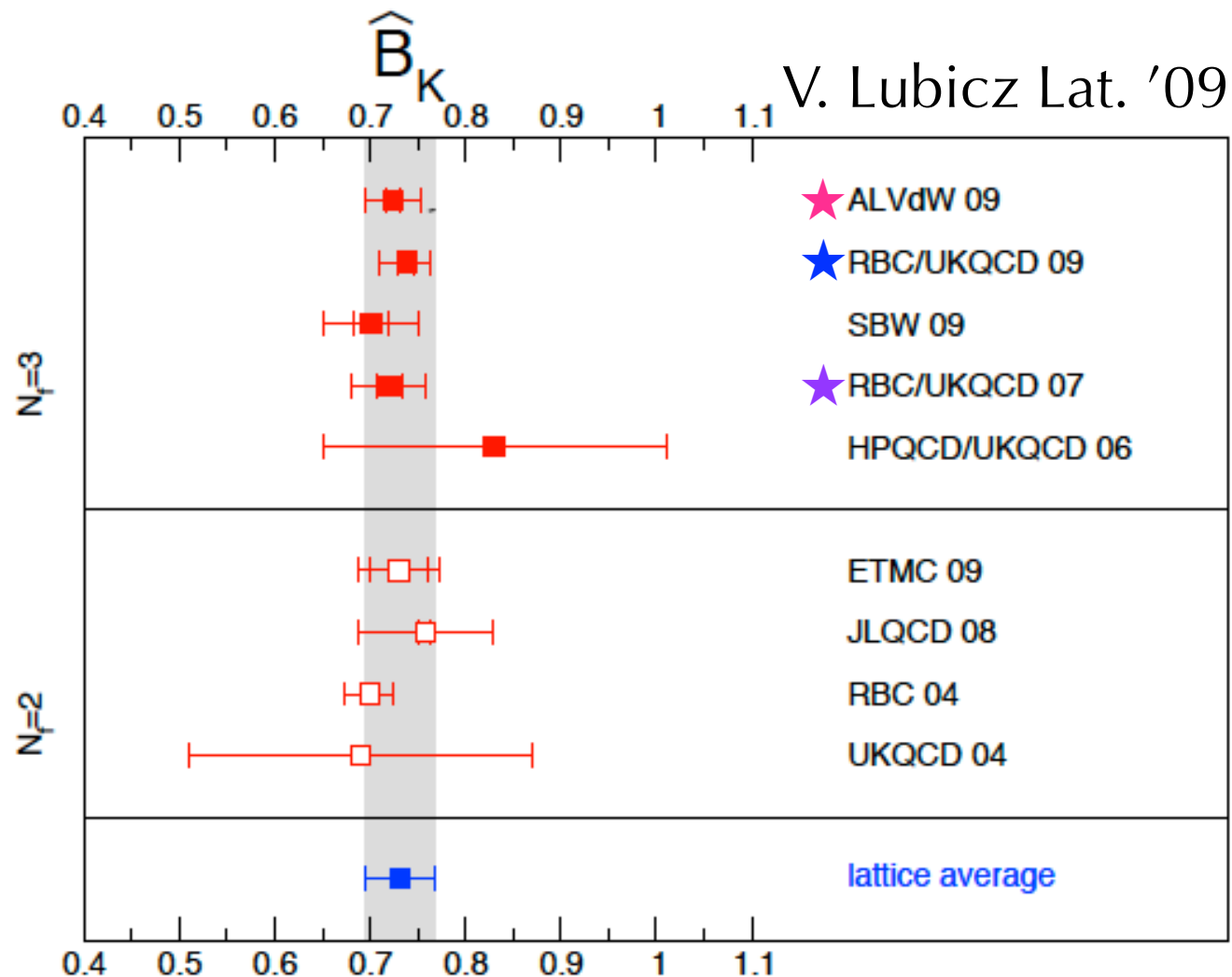


- until recently, led to best determination of the CKM matrix element $|V_{us}|$ with a total error of 0.5%

- In April, RBC/UKQCD posted an updated result with reduced uncertainties to the arXiv, but members of the BNL HET group were unable to contribute to this improved calculation due to limited human resources

Neutral kaon mixing parameter B_K

- ◆ The amount of direct CP-violation in the neutral kaon system, ε_K , is known to sub-percent precision, and constrains the apex of the CKM unitarity triangle
- ◆ Two groups with members in the BNL HET group are independently calculating B_K with different lattice formulations

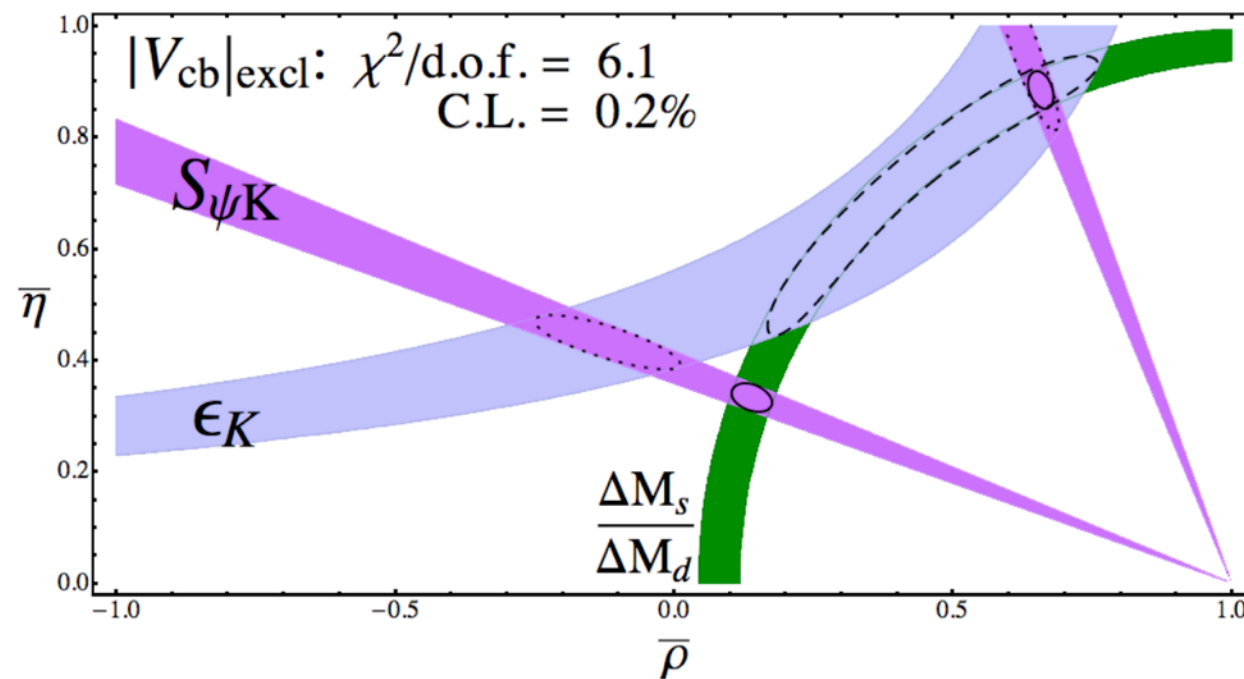


- ❖ 2007: RBC/UKQCD published the first precise three-flavor lattice calculation of B_K with a 6% accuracy
- ❖ May 2009: Aubin, Laiho, & RV obtained the first three-flavor lattice determination from data at two lattice spacings with a ~4% error
- ❖ The independent result of ALVdW using a different lattice formulation confirmed that of RBC/UKQCD
- ❖ Lattice 2009: RBC/UKQCD presented a preliminary result obtained from two lattice spacings with a reduced ~4% error

Status of B_K constraint on the unitarity triangle

- ✦ Until recently, the uncertainty in the ϵ_K band was primarily due to the uncertainty in lattice QCD calculations of the hadronic matrix element B_K
- ✦ The improved recent lattice determinations of B_K revealed a 2-3 σ tension between the ϵ_K band and the other UT constraints [Lunghi & Soni, arXiv:0803.4340]

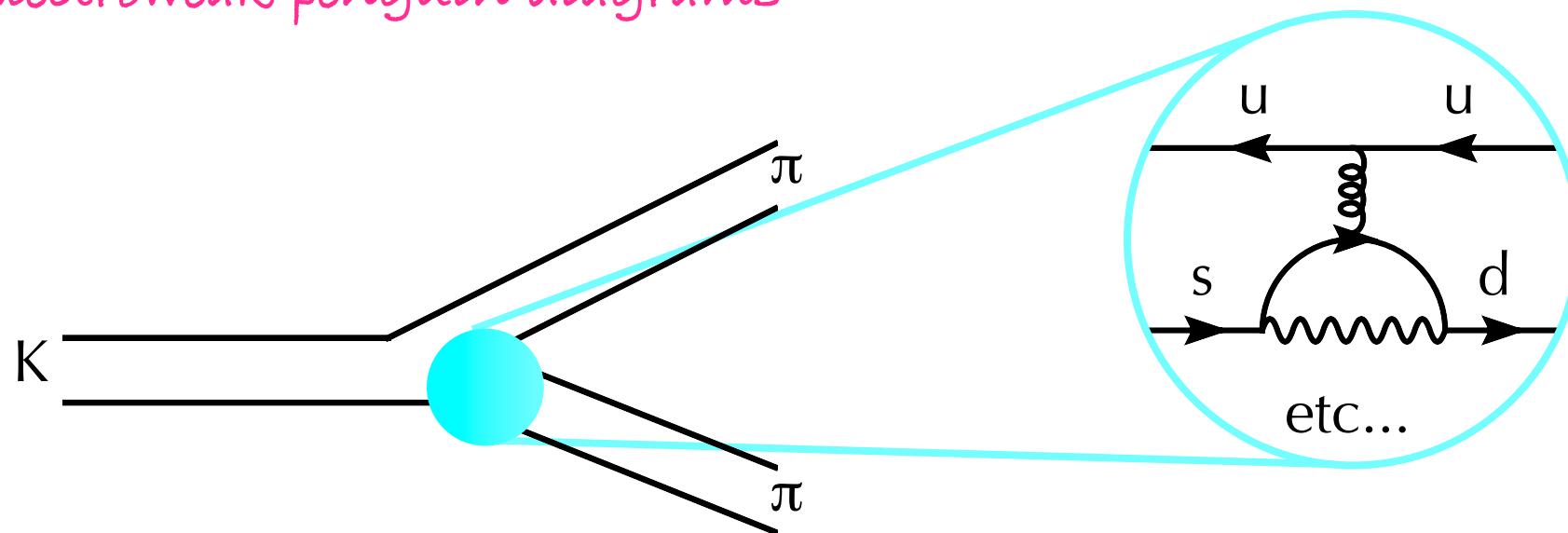
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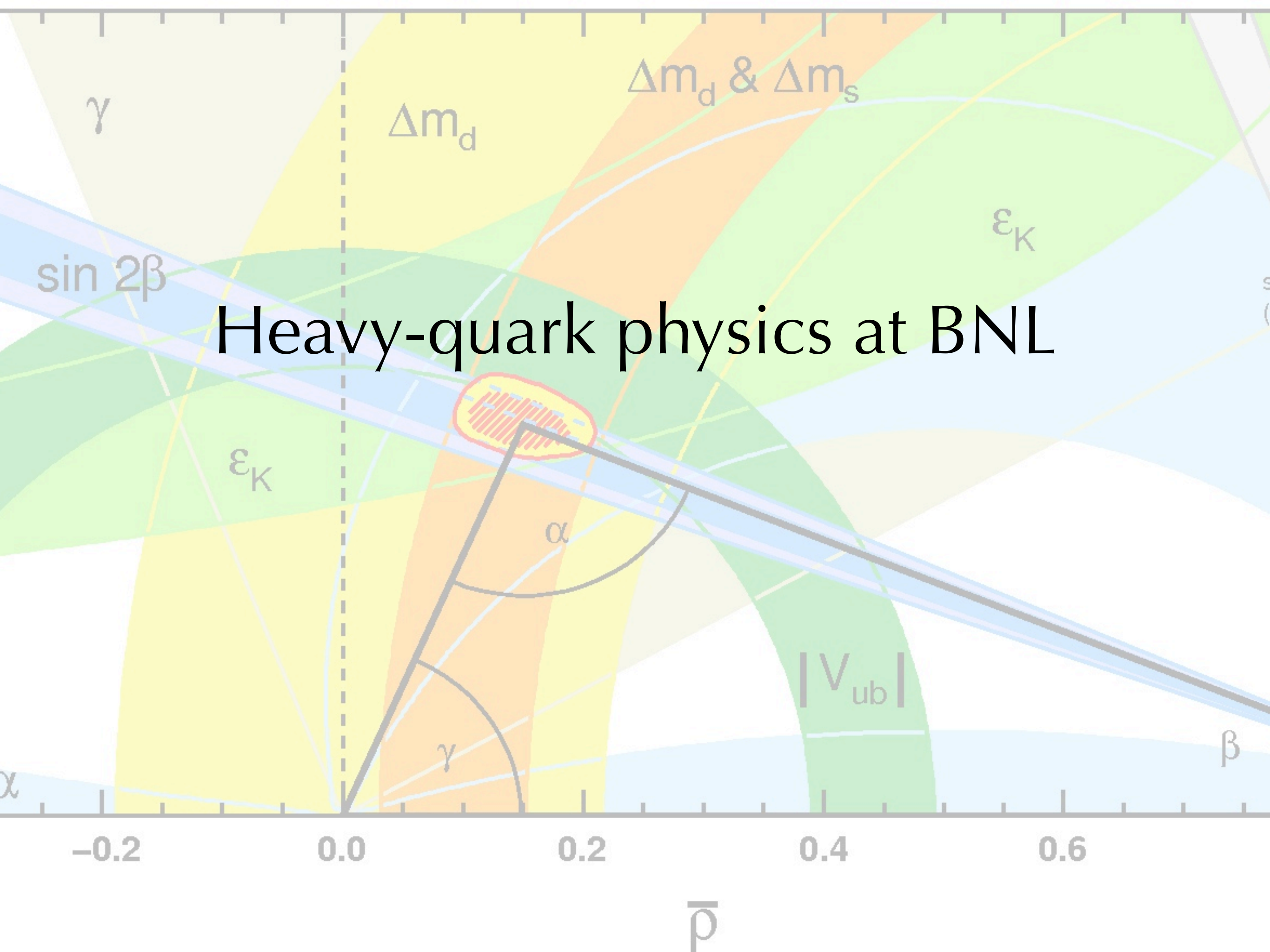
- ✦ May be a hint of new physics in neutral kaon or B-mixing...

$K \rightarrow \pi\pi$ decay

- ◆ Now that BK is no longer the dominant uncertainty in the ϵ_K band, both **RBC/UKQCD** and **Laiho & RV** are independently calculating direct CP-violation $K \rightarrow \pi\pi$ decay
 - ❖ Technically challenging and has not yet been done for three dynamical quark flavors
 - ❖ May be particularly sensitive to new physics because it receives contributions from 1-loop electroweak penguin diagrams



- ◆ Needed to understand origin of the $\Delta I=1/2$ rule ($A_2/A_0 \sim 1/22$)
- ◆ Especially important given the hints of new physics!
 - ❖ Almost all constraints on the CKM unitarity triangle come from B meson (semi-) leptonic decays and mixing, so **must test whether observed CP violation is the same in the kaon sector and the B-sector**



Heavy-quark physics at BNL

RBC/UKQCD heavy-light physics program

- ◆ Until recently, **only two groups calculating B-meson hadronic weak matrix elements** needed for CKM matrix element determinations and unitarity triangle fits using three dynamical quark flavors
 - ❖ Both groups use the same staggered gauge configurations generated by the MILC collaboration, so their **results are not wholly independent**
- ◆ During this past year we have **begun a heavy-light physics program using domain-wall light quarks and relativistic c- and b-quarks**
 - ❖ Are first focusing on simpler quantities such as decay constants and mixing parameters
 - ❖ Will then move on to more challenging semileptonic form factor calculations
- ◆ Expect errors in ~1-2 years to be competitive with current Fermilab/MILC and HPQCD results
 - ❖ *Will provide an essential crosscheck of phenomenologically-important quantities*

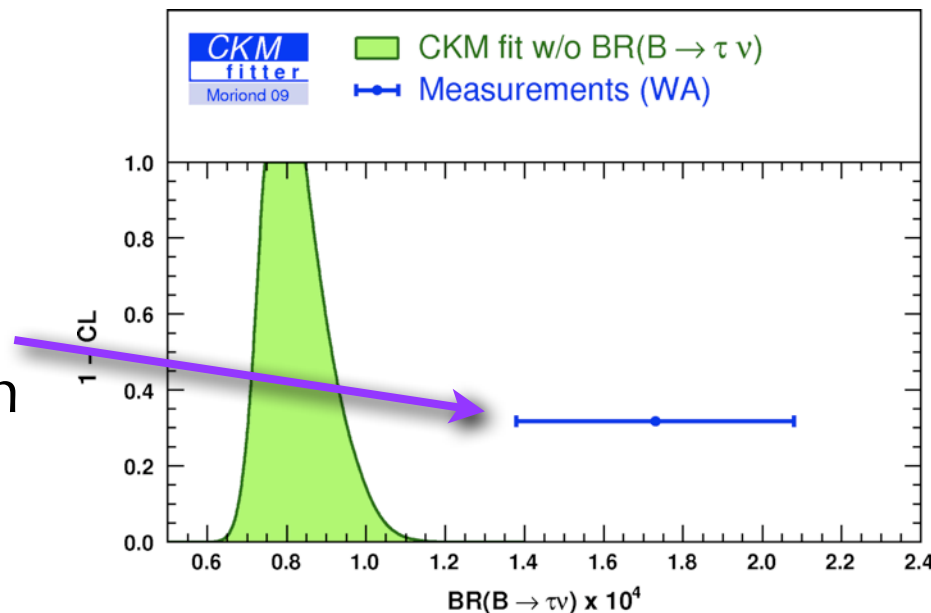
D-meson leptonic decay constants

- ◆ Comparison between lattice calculations of f_D and f_{D_s} and experimental measurements provide **good tests of lattice methods**:
 - ❖ Leptonic D and D_s decays occur at tree-level in the Standard Model, so new physics contributions are expected to be small
 - ❖ CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$ are well-constrained within the Standard Model by unitarity
- ◆ Currently working on calculation of f_D and f_{D_s} with our RBC colleagues at Columbia
 - ❖ Using **same relativistic action for c-quarks as we will for b-quarks**
 - ❖ Agreement with experiment will validate our method and bolster confidence in future calculations of $f_{B(s)}$ and other B-meson matrix elements

B-meson leptonic decay constants

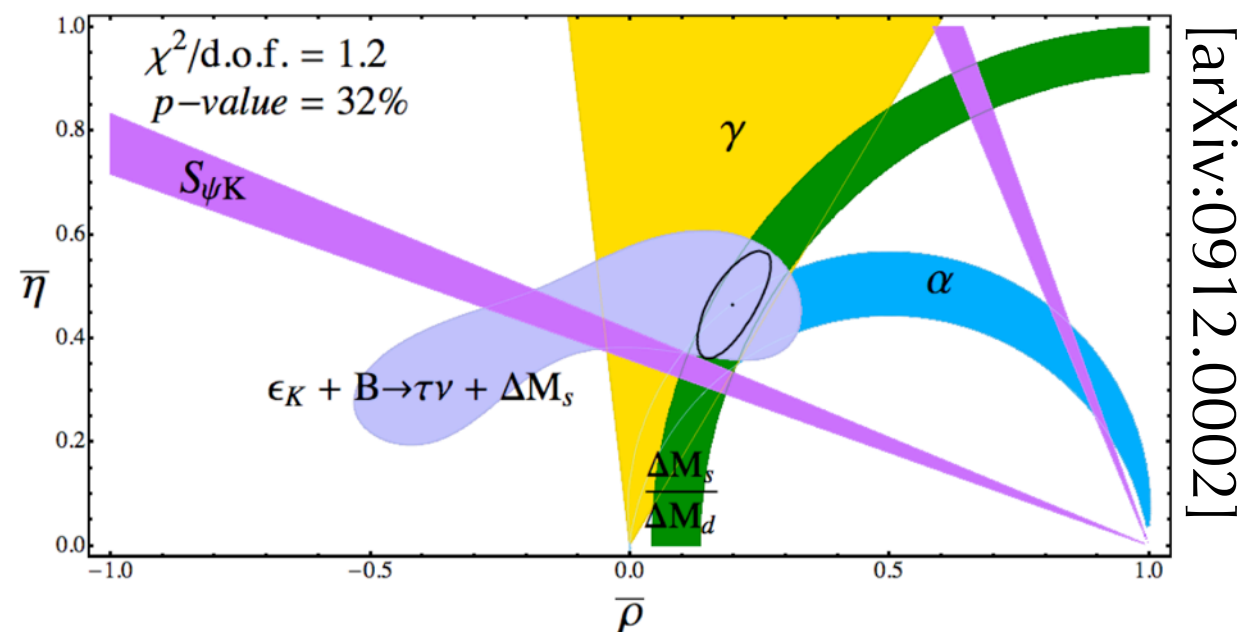
Improved lattice determinations of f_B are needed for many phenomenological applications

- ◆ $B \rightarrow \tau \nu$ decay can **probe charged Higgs** if f_B is known
- ❖ Currently a **2.4σ** tension between experiment and the SM prediction



- ◆ **Lunghi & Soni** recently proposed an alternative method to constrain the apex of the CKM unitarity triangle which does not require inputs from semileptonic decays

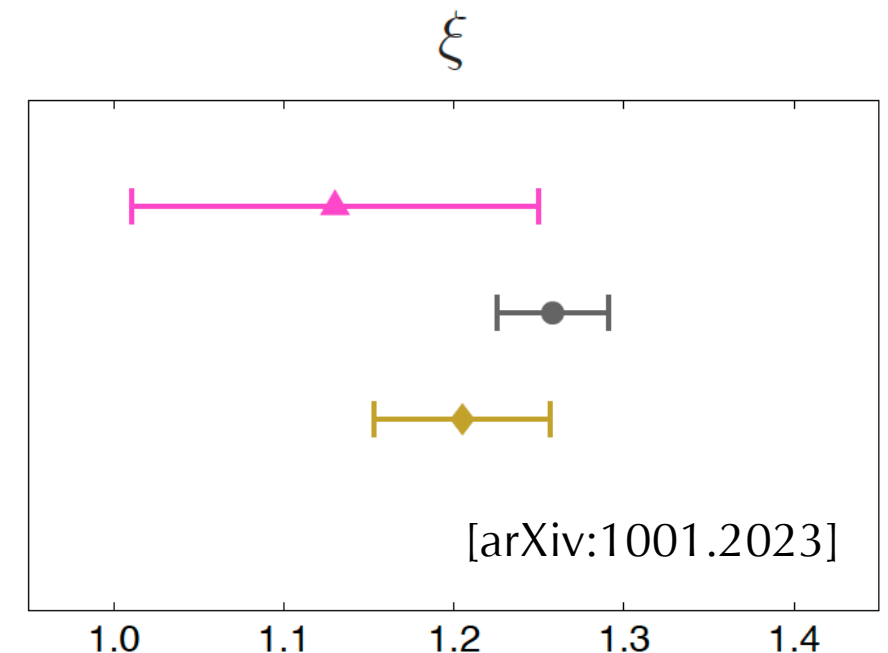
- ❖ Avoids concern of $\sim 2\sigma$ tensions between inclusive and exclusive determinations of $|V_{ub}|$ & $|V_{cb}|$
- ❖ New approach requires f_B as input



Neutral B-meson mixing

- ◆ Combining the ratio of neutral B-mixing matrix elements (ξ) with exp. measurements of the B_d and B_s oscillation frequencies constrains the apex of the CKM unitarity triangle
- ◆ **Since the constraint from B-mixing is perpendicular to that from $\sin(2\beta)$, B-mixing plays a key role in searching for new physics in the flavor sector**
- ◆ We are calculating the B-meson and decay constants and mixing parameters using domain-wall light quarks and both static and relativistic b-quark formulations
 - ❖ Posted our first publication demonstrating the viability of the method in January
 - ❖ Will reduce the statistical and systematic errors in a subsequent publication and expect to obtain a competitive final result

▲ RBC/UKQCD
● HPQCD [14]
◆ FNAL-MILC [15]



Ultimately we plan to move on to the $B \rightarrow D^* l \nu$ form factor, which is needed to extract $|V_{cb}|$, and other B-meson weak matrix elements ...

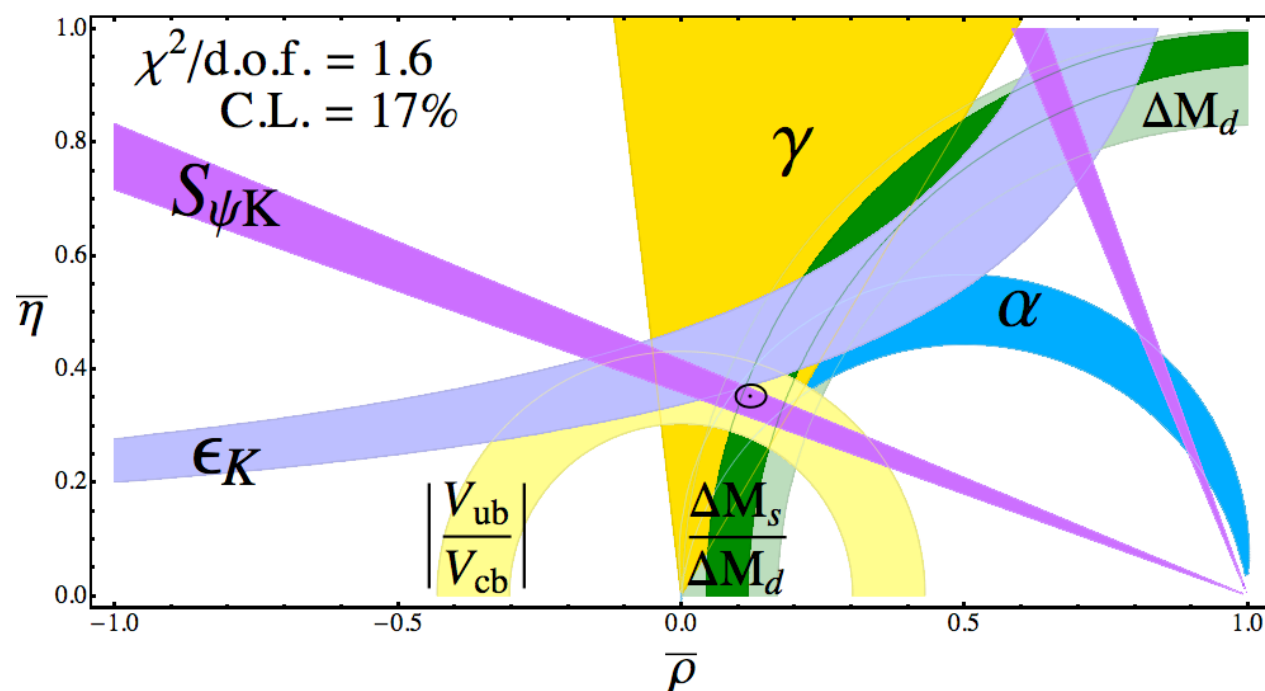
Summary and outlook

- ◆ Although no “smoking gun” of new physics in the flavor sector, there are several hints that one should keep an eye on, such as the tension between the ε_K band and the remaining CKM unitarity triangle constraints
- ◆ Members of the BNL high-energy theory group are attacking several of the most important weak-matrix elements for CKM phenomenology
 - ❖ Already well-established program in kaon physics has lead to the current best calculations of the $K \rightarrow \pi \nu$ form factor and neutral-kaon mixing parameter B_K
 - ❖ Now turning our attention to the more challenging target of $K \rightarrow \pi\pi$ decay
 - ❖ Also developing a B- and D-meson physics program using domain-wall light quarks
 - ❖ Posted first paper on the B-meson decay constants and mixing parameters this year
- ◆ BNL HET group has **expertise in both lattice gauge theory and flavor phenomenology**, so we have numerous ideas for additional projects (e.g. $B \rightarrow D^* l \nu$ form factor and $|V_{cb}|$)
 - ❖ We have lots of computing resources, and are *only limited in our scope by the number of personnel!*

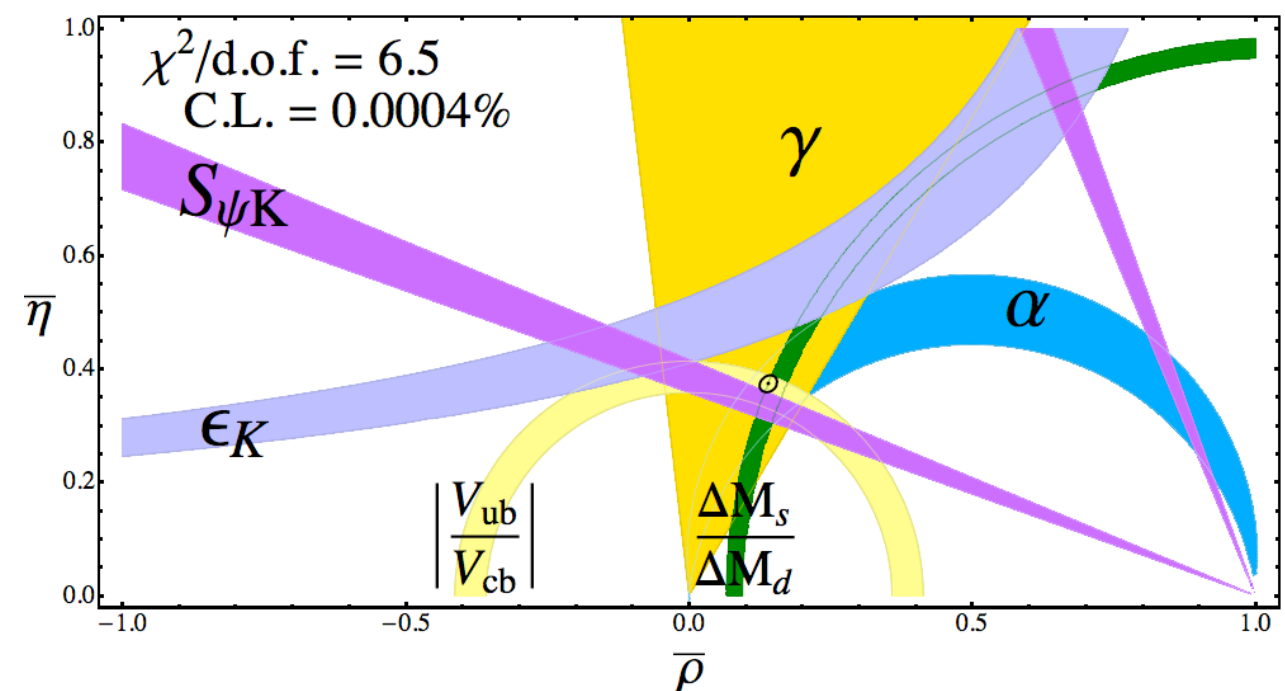
Potential impact of future lattice calculations

- ◆ To illustrate the potential impact of high-precision lattice calculations, consider the CKM unitary triangle:
 - ❖ Reduce the lattice uncertainties the weak matrix element inputs to 1% (central values fixed), but keep the experimental uncertainties at the current level

NOW



~5 YEARS



- ◆ Lattice QCD at BNL is poised to play a key role in discovering new physics in the flavor sector!